How to Disregard Irrelevant Stimulus Dimensions: Evidence from Comparative Visual Search

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Abstract

To what extent is it possible to disregard stimulus dimensions that are irrelevant to a certain task? This question was tackled in three experiments using the paradigm of comparative visual search. Reaction times and eye-movement data were recorded in order to study the cognitive processes in this series of tasks. For the data analysis, task-specific variables were defined and their values computed across subjects and tasks. The results show that on the basis of top-down processes only, it is easier to ignore shape information, and that disregarding color information requires additional bottom-up processes.

1. Introduction

Investigating the processing of different dimensions of visual objects has been a central issue in perceptual studies at all times. One question within this subject area concerns the separability or integrality of stimulus dimensions: Do variations in an irrelevant dimension (e.g., color) affect the perceptual processing of another relevant dimension (e.g., form)? In other words, are subjects able to disregard irrelevant stimulus dimensions? This issue has been investigated from within various experimental paradigms.

One of these paradigms is visual search [1 – 3]. In the standard task, subjects have to state whether or not a display contains a designated object. This target differs from distractors with respect to a single dimension such as color or shape (e.g. a red X among black Xs) or several dimensions such as color and shape (e.g. a red X among red Os and black Xs). In a typical experiment that was concerned with the consequences of irrelevant stimulus dimensions [4], subjects had to search a display for a specific target (circle) among distractors (diamonds) and to state whether a line segment inside the target was horizontal or vertical. When all objects were of the same color, this task was very easy to accomplish since the discrepant object appeared to "pop out" from among the distractor objects. In effect, reaction times were rather short and virtually independent of the number of distractors. However, when changing the experimental setup so that one of the distractors differed in color from both the target and the other distractors, reaction times increased. The additional discrepant object seemed to compete for attention with the actual target. The same result pattern was obtained for a color target and form as the irrelevant dimension [5]. To sum up: The observations from visual search lead to the conclusion that subjects are not able to disregard the irrelevant color or form dimension.

Another experimental approach is the same-different paradigm [6 – 9]. In a same-different task, two stimuli are presented to the subject either simultaneously or in succession, and the subject has to decide whether they are the same or different with respect to certain relevant stimulus dimensions. In a classical experiment [10], stimuli varied along three dimensions: color (red or blue), form (square or circle) and tilt (the figure contained an ascending or a descending line). A mismatch in at least one specified characteristic should lead to a "different" answer. Under "different" conditions all possible stimulus dimensions and their combinations were defined as relevant. An analysis of the "same" answers showed that reaction times were faster when the stimuli were identical with respect to the irrelevant dimensions than when they were different. If, for example, the subjects had to decide whether or not two stimuli had the same color, a "same" response was faster when their forms were also identical. Findings like these indicate that, as in visual search, subjects cannot ignore irrelevant dimensions.

The two paradigms share the general approach to a practical solution of the problem. Both paradigms proceed from the basic question if irrelevant stimulus dimensions take a *negative* effect on the processing of relevant ones. In their attempt to answer this question, both approaches start by determining baseline values for dependent variables such as reaction time or error rate without varying any irrelevant dimensions. After that, values for dependent variables are measured under conditions that include one or more irrelevant dimensions. A *decrease* in performance indicates that subjects unable to completely disregard any irrelevant dimensions.

Our approach is somewhat different. We proceed from the question if certain experimental manipulations take a *positive* effect on the subjects' ability to disregard the irrelevant dimension. In order to answer this question, values for dependent variables are determined using a task where two stimulus dimensions (a relevant and an irrelevant one) have to be attended to. Subsequently, the experimental task is manipulated in such a way that subjects may ignore one of the dimensions. An *increase* in performance indicates that subjects are able to disregard irrelevant dimensions (at least partially).

In order to realize such an approach, a relatively complex task is required in which subjects cannot separate irrelevant from relevant stimulus dimensions offhand. Therefore, we employed a relatively novel paradigm of investigation. It is termed *comparative visual search*, because subjects have to search for the only difference between two halves of a display [11 - 13]. The display presents a randomly generated two-dimensional object array which is divided into two halves. Each half contains a number of simple geometrical objects of three different colors and three different forms. The display halves are identical with respect to object number, object location, object form, and object color - except for exactly one mismatch between corresponding objects in either form or color (see Figure 1 for an example). The stimulus dimension that constitutes the mismatch shall be referred to as the relevant dimension, the other one as the irrelevant one. Immediately on detecting the mismatch, subjects are to press a mouse key.

Comparative visual search can be described as a combination of visual search and a same-different task. Globally, the subjects' task is to search the display for the stimulus pair that differs with respect to a particular stimulus dimension. Locally, the subjects compare individual stimulus pairs or pairs of stimulus clusters and decide whether they are the same or different. Undoubtedly, comparative visual search is more complex than either a standard visual search task or a same-different task. In comparative visual search, subjects have to scan the set of objects sequentially. With each step, they have to keep in mind the features of a subset of objects to be compared; they have no advance representation of the target; they repeatedly have to switch between corresponding display halves; and they have to keep track of which areas have already been processed. Obviously, this task is suitable for our purposes, since the subjects are not able to distinguish the relevant from the irrelevant dimension at first sight.

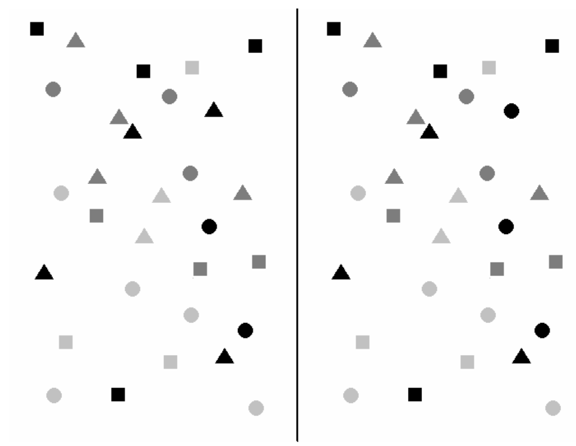

Figure 1: Example of a randomly generated stimulus picture containing a form mismatch

To make a complex task like comparative visual search give evidence, dependent variables are required that are more sophisticated than global reaction times and overall error rates. The use of such variables is rendered possible by recent developments in measurement technique and methodological improvements in the study of cognitive processes. One of these advances is the development of new eye tracking systems that enable high resolution on-line measurement of a viewer's current gaze position. On the assumption that objects being fixated are being processed (eye-mind assumption) and that the fixated object is processed as soon as possible and as far as possible (immediacy assumption) eye movement data may yield important information about cognitive processes [14]. Unlike reaction times, eye movements enable researchers to reconstruct the time course of processing, that is, to find out which objects are attended at what time during visual search or comparison.

Will certain kinds of experimental manipulations take a positive effect on disregarding an irrelevant stimulus dimension? How can this question be tackled in practice? In the paper at hand, we describe three experiments featuring different conditions. In Experiment 1, baseline values for reaction times and eye movements are gathered while subjects have to attend to both the relevant and the irrelevant stimulus dimension. Experiment 2 is designed to study whether or not subjects benefit from verbal information about the relevant dimension (i.e., the type of mismatch). If comparative search is more efficient under these conditions (compared to Experiment 1), this must be due to top-down attentional processes since the visual stimuli do not differ at all from those of Experiment 1. In Experiment 3, the irrelevant dimension is held constant in order to study any facilitating effects of bottom-up processes on subjects' performance in comparative visual search, compared to Experiment 2. Additionally, the experiments permit us to compare color and form as irrelevant dimensions. Are subjects equally effective in filtering out color and form? Or are top-down processes sufficient to disregard one of the two dimensions while bottom-up processes help to disregard the other one? Any such disparities could be interpreted as indicating differences in the cognitive processing of color and form.

Thus, the independent variables are the *type of mismatch* (i.e., whether the difference between corresponding objects is in color or in form) and the factor *experiment* for the comparisons between the experiments. The dependent variables are reaction time and eye movement data: As mentioned above, *reaction time* (RT) is a global measure of the subjects' efficiency in a visual search or comparison task. RT decreases if the search gets more efficient, i.e., if subjects are able to disregard the irrelevant stimulus dimension.

The analysis of eye movements is based on three "classical" and two derived variables: The first "classical" variable of eye-movement research is *fixation duration* (FD). FD is known to indicate quantitative as well as categorial differences in mental effort [15, 16]. In comparative visual search, FD likely depends on the amount of information that has to be encoded at any step. Therefore, it should decrease if the subjects are able to disregard the irrelevant stimulus dimension. The second "classical" variable is *saccade length* (SL), defined as the visual angle between the starting and landing points of a saccade. Longer saccades signify a more parsimonious fixation strategy. Therefore, longer saccades would indicate that the irrelevant dimension can be disregarded. As a third "classical" variable, we registered the *number of fixations* (NF) that the subjects performs prior to detecting the difference. If the subjects are able to disregard the irrelevant dimension, NF should decrease.

Previous research [11] has shown that the time required to detect a mismatch does not only depend on the speed of search and comparison, but also on the *additional search time* (AT) caused by missing the target. The analysis of pre-tests has led to the following definition of "missing the target:" A target passage is registered whenever the subject's gaze position gets closer than 2 degrees of visual angle to a target object and - with the next fixation - to the corresponding object in the other half. It goes without saying that more than one target passage can be found during the same search process. A target miss is registered if the gaze position has left the target area after passing it and the subject does not press the button within the following 2 seconds. AT is the amount of time being "wasted" by missing the target. It is measured as the interval between the first and the final target passage so that AT has the value 0 if the target is not missed at all. In the context of comparative visual search, AT can be viewed as a measure of the subjects' target detection capability. Therefore, the better subjects are at disregarding one stimulus dimension, the smaller we expect the value of AT to be.

As a measure of the efficiency of memorization and comparison which is neither influenced by AT nor by the manual reaction, defining an appropriate additional variable seems useful. We have observed that subjects scan the display from the top to the bottom or vice versa (at least until they feel to have missed the target, in which case the search process tends to lose its regular structure). Consequently, we introduced a variable named *speed of processing* (SP). It is defined as the mean vertical distance between two successive fixations divided by the respective inter-fixation time interval, accounting only for fixations prior to he first change in the vertical search direction. In order to exclude any influence of orientation or verification processes, SP is neither measured during the first second of a trial nor during the final target passage at the end of a trial. Presumably, SP should increase if the subjects restrict their attention to one of the two stimulus dimensions. To summarize: The only independent variable within each experiment is *type of mismatch*, and the one for comparisons between experiments is *experiment*. The dependent variables are RT, FD, SL, NF, AT, and SP.

2. Experiment 1

The purpose of Experiment 1 was to assess the dependent variables when both stimulus dimensions had to be attended to because the subjects were not informed in advance about the type of mismatch. Under these circumstances, neither top-down nor bottom-up filtering processes were possible. Therefore, the results provide a baseline against which subsequent results could be tested to answer the question if experimental manipulations help to ignore irrelevant stimulus dimensions.

Since in each trial the subjects did not know whether the mismatch was going to be in color or in form, we have no reason to assume that SP depends on the type of mismatch unless the subjects have "anticipative" skills or analyze dimensions in a strictly serial fashion. If, for example, subjects searched the display for a color mismatch first and for a possible form mismatch afterwards, we should find shorter RT with regard to color mismatches. However, as this kind of strategy is not efficient, subjects are unlikely to apply it.

For the same reason we did not expect to find an effect of the type of mismatch on FD or SL before the final target passage. However, NF and AT could be different for color and form mismatches if one type of mismatch is harder to detect than the other. This would be the case if the chosen color and form differences were not equally detectable or if people employed different strategies in analyzing objects for their color and form. Problems in finding the difference would lead to a higher proportion of target misses and therefore to an increase in NF and AT, and thus in RT.

2.1. Method

Sixteen subjects were recruited at Bielefeld University. All had normal or corrected-to-normal vision. None of them was color blind or had pupil anomalies. All subjects were paid for their participation.

Stimuli were shown on a 17" ViewSonic7 monitor with a refresh rate of 72 Hz and a resolution of 640 by 480 pixels. Computer mouse buttons were used to record the subjects' response.

Eye movements were measured by means of a non-invasive imaging eye tracking system. The OMNITRACK 1 system uses an ISCAN RK-416PC pupil tracking board and two miniature infra-red video cameras that yield on-line information about pupil and head movements, such that slight head movements do not impair measurement accuracy. Fixation points on the screen are calculated from the camera data at a frame rate of 60 Hz. Only fixations that last for at least five frames (i.e. 83 ms) are recorded. The recorded data comprise time of occurrence, duration, screen coordinates, and actual pupil size. The spatial precision of the system lies within a range of 0.7 to 1.0 degrees of visual angle, but the resolution of measurement was improved to 0.5 degrees (i.e. 0.6 cm or 12 pixels) by the use of a neural network interface [17]. Prior to experimentation a short calibration procedure had to be performed which lasted for about 30 seconds. Additionally, the system was recalibrated after every tenth stimulus presentation in order to compensate for possible sliding of the head set due to subjects' head movements.

Every stimulus picture consisted of two display halves, each of them 11 degrees wide and 16 degrees high. In each half, 30 simple geometrical objects were presented on a black background. Three forms (triangle, square, or circle) and three colors (fully saturated blue, green, or yellow) were used. Frequencies of the different colors and forms were balanced in each display half. The size of the objects was about 0.7 degrees in diameter. Object locations were randomly generated with one exception: No object overlap or contiguity was allowed. The display halves were identical with respect to location, color, and form of the objects, except for the target that had a difference either in color or in form.

A written instruction informed the subjects about the composition of the stimulus pictures and their task. Subjects were told to press a mouse button as soon as they had detected the mismatch between the two display halves. After a few practice trials, the eye tracker system was calibrated and the experimental trials began. Each subject viewed 50 randomly generated stimulus pictures and the system was recalibrated after every tenth trial. 25 of the stimulus pictures had a mismatch in color and 25 had a mismatch in form. The subjects were not instructed about when to expect which type of mismatch. For each trial eye movements and reaction time were registered.

2.2. Results and Discussion

RT was significantly shorter with respect to color mismatches (9904 ms) than with respect to form mismatches (11997 ms), $t(15) = 2.94$, $p < 0.05$. As predicted, type of mismatch had no significant effect on SP (45.59 pixels/s for color mismatches and 45.30 pixels/s for form mismatches), on FD (208.75 ms for color mismatches and 207.46 ms for form mismatches), and on SL (55.18 pixels for color mismatches and 55.13 pixels for form mismatches). Therefore, these three variables do not account for the RT difference. AT indicates the amount of additional search time caused by missing the target. Here a form mismatch “costs” 2855 ms as compared to 1248 ms for a color mismatch. This difference was significant, $t(15) = 3.04$, $p < 0.01$. This means that AT accounted for 1607 ms of the overall RT difference of 2093 ms. At this point the question arises whether the remaining 486 ms reflect a systematic influence or should better be attributed to the experimental error, or “noise.” Since the RT differences did not depart significantly from the AT differences, $t(15) = 1.22$, $p > 0.2$, it seems plausible to argue that the variance in RT is due to AT. NF was also affected by the type of mismatch. Searching for a color mismatch took 31.76 fixations compared to 39.66 for searching for a form mismatch, $t(15) = 3.00$, $p < 0.01$, which is probably also due to the additional fixations caused by missing the target. The results across experiments and conditions, including mean values and standard error, are shown in Figures 2 to 7.

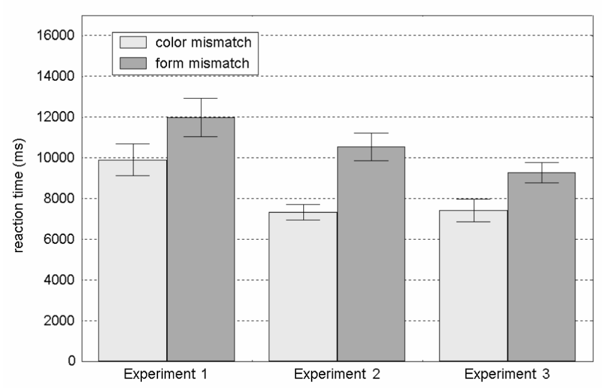

Figure 2: Mean reaction time (RT)

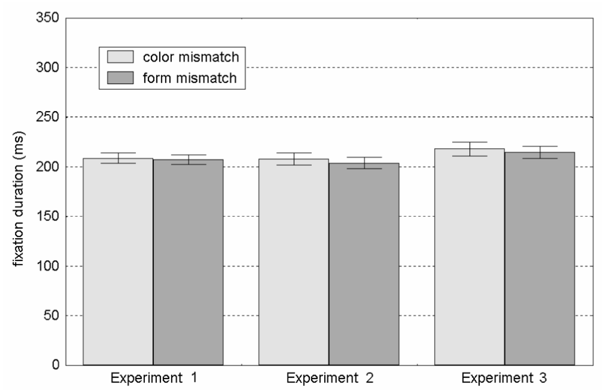

Figure 3: Mean fixation duration (FD)

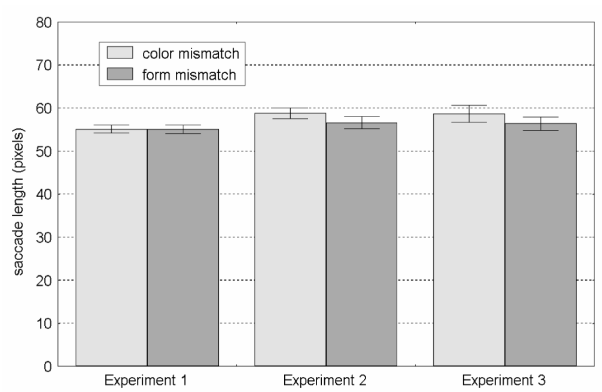

Figure 4: Mean saccade length (SL)

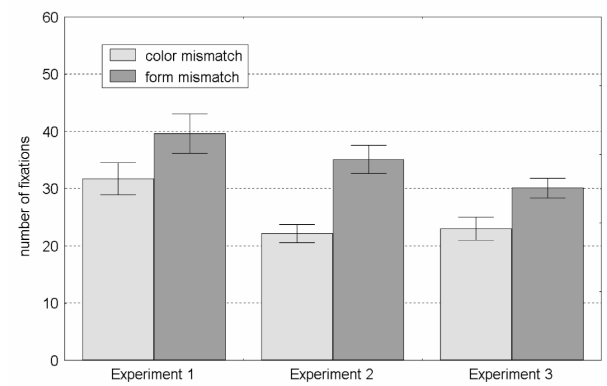

Figure 5: Mean number of fixations per trial (NF)

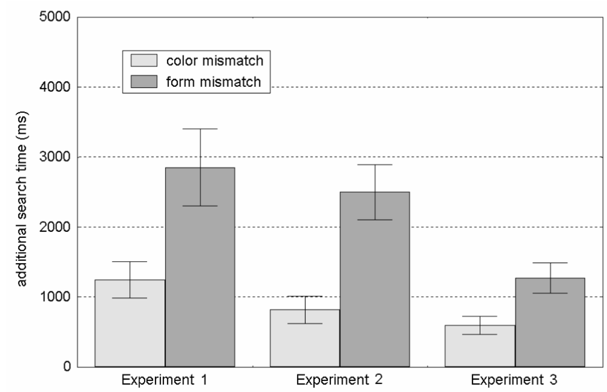

Figure 6: Mean additional search time caused by missing the target (AT)

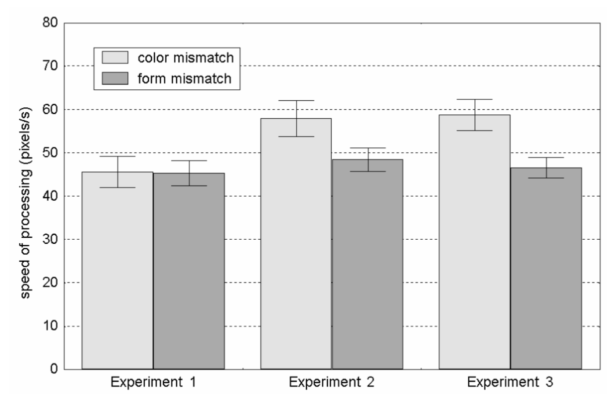

Figure 7: Mean vertical speed of processing (SP)

With that, we are able to outline the differences between color and form search in Experiment 1: When the subjects are not informed about the type of mismatch, detecting a form target is more difficult. More specifically, subjects are more likely to "miss" a form mismatch than a color mismatch. Missing the target forces the subject to continue searching. This extra search takes time (AT) and additional fixations (NF), causing an increase in RT.

3. Experiment 2

Experiment 2 was designed to investigate whether top-down control enables subjects to filter out the irrelevant stimulus dimension (color or form). As a straightforward way to make subjects attend to the relevant stimulus dimension and to disregard the irrelevant one, we used a verbal instruction that informed the subjects in advance when to expect which type of mismatch. An efficiency gain would be indicated by a significant decrease in RT, FD, NF and AT and an increase in SL and SP from Experiment 1 to Experiment 2 (in technical terms, these expectations correspond to a significant main effect of the factor experiment).

Another objective of Experiment 2 was to study whether color and form can be ignored equally effectively. This would be the case if the changes in the efficiency parameters are independent of the type of mismatch. If, however, the efficiency gain is more pronounced for color search than for form search or vice versa (which would correspond to a significant interaction between the factors experiment and type of mismatch), this could be taken as suggesting that top-down control of attention depends on the choice of relevant/irrelevant dimensions.

3.1. Method

A new group of twenty subjects with normal or corrected-to-normal vision were recruited at the University of Bielefeld and paid for their participation. As in Experiment 1 none of them was color blind or had pupil anomalies.

Apparatus, stimuli, and procedure were identical to Experiment 1 with the following exceptions: The trials were arranged in 6 blocks. Each block consisted of 10 trials, with either only color or only form mismatches. Between blocks, *the experimenter told the subjects which type of mismatch to expect* during the next block.

3.2. Results

As in Experiment 1, RT was significantly shorter with respect to color mismatches (7330 ms) than with respect to form mismatches (10541 ms), $t(19) = 5.45$, $p < 0.001$. This constitutes a difference of 3211 ms. Type of mismatch had no effect on FD (208.04 ms for color mismatches and 203.91 ms for form mismatches) but showed a slight tendency towards shorter fixations for form mismatches, $t(19) = 1.74$, $p = 0.097$. SL was longer when subjects searched for a color mismatch (58.80 pixels) than when they searched for a form mismatch (56.65 pixels), $t(19) = 2.60$, $p < 0.05$). SP was faster for color mismatches (57.92 pixels/s) than for form mismatches (48.47 pixels/s), $t(19) = 3.28$, $p < 0.005$. Again, AT was shorter for color mismatches (818 ms) than for form mismatches (2500 ms), $t(19) = 4.14$, $p < 0.005$, and NF was lower for color mismatches (22.17) than for form mismatches (35.15), $t(19) = 5.96$, $p < 0.001$. In contrast to Experiment 1, the AT difference of 1682 ms did not account for the RT difference of 3211 ms completely: RT differences and AT differences were unequal, $t(19) = 3.58$, $p < 0.005$. Thus it is plausible to assume that the extra time is caused by the different SP and SL values. The results are shown in Figures 2 to 7.

Summing up: Even if subjects know in advance which kind of mismatch to expect, form search seems to be harder to accomplish than color search, at least with these particular colors and forms. Search for a difference in form is slower than color search; also, the probability of overlooking a mismatch is higher with forms than with colors. Thus, the increase in RT is due to longer AT (that goes together with higher NF) as well as lower SP and SL.

To analyze the data with respect to efficiency gains and the potential difference between color and form as irrelevant dimension, analyses of variance on RT, FD, AT, and SP with the within-subjects factor type of mismatch (color vs. form mismatch) and the between-subjects factor experiment (Experiment 1 vs. Experiment 2) were carried out. For the sake of completeness both main effects and the interaction will be reported for all dependent variables, although focus is on the differences between the experiments, that is, differences in efficiency.

The type of mismatch had significant effects on RT, $F(1;34) = 33.55$, $p < 0.001$, on NF, $F(1;34) = 38.06$, $p < 0.001$, on SP, $F(1;34) = 7.98$, $p < 0.01$ and on AT, $F(1;34) = 25.24$, $p < 0.001$. In detail, a color target was detected faster (8617 ms) than a form target (11269 ms). NF was higher for form mismatches (37.40) than for color mismatches (26.96). SP was higher for color mismatches (51.76 pixels/s) than for form mismatches (46.89 pixels/s). AT was shorter when search was directed at a color mismatch (1033 ms) than when it was directed at a form mismatch (2678 ms). Type of mismatch slightly missed significance on SL, $F(1;34) = 3.99$, $p = 0.054$, but the tendency indicated longer saccades for color mismatches (56.99 pixels) than for form mismatches (55.89 pixels). Type of mismatch did not affect FD (208.40 ms for a color mismatch versus 205.69 ms for a form mismatch).

Also the factor experiment had a significant effect on RT: Average RT in Experiment 2 (8936 ms) was faster than that in Experiment 1 (10950 ms), $F(1;34) = 5.26$, $p < 0.05$. The only other variable that showed an effect of the factor experiment was NF. NF was lower in Experiment 2 (28.66) than in Experiment 1 (35.71), $F(1;34) = 4.80$, $p = 0.035$.

The only significant interaction effect was the one on SP, $F(1;34) = 7.07$, $p < 0.05$. Simple effects analyses indicated that the factor experiment had an effect only in color mismatch trials, $F(1;34) = 4.70$, $p < 0.05$, while type of mismatch had an effect only in Experiment 2, $F(1;34) = 16.93$, $p < 0.001$. In other words: SP was identical for color and form mismatches in Experiment 1 and for form mismatches in Experiment 2. The only condition that differed from the others was search for color mismatches in Experiment 2: SP was higher in this case. The interaction effect for SL did not reach significance but showed a tendency in the predicted direction, $F(1;34) = 3.65$, $p = 0.065$.

How are these results to be understood in the light of the assumptions? Two efficiency measures, namely RT and NF, decrease from Experiment 1 to Experiment 2. Obviously, the subjects do benefit from the information about the type of mismatch. They are able to – at least in part - disregard an irrelevant stimulus dimension irrespective of the type of mismatch. On the other hand, the interaction between type of mismatch and experiment for SP and the tendency for SL indicate that the color mismatch trials benefit from information about the type of mismatch while form mismatch trials do not. In other words: It seems easier to filter out irrelevant form information via top-down processes than irrelevant color information.

4. Experiment 3

It must be pointed out, though, that "a priori" information about the relevant dimension does not necessarily preclude the irrelevant dimension from being processed. Rather, the effects of a verbal instruction are restricted to those attentional mechanisms that are controlled by top-down processes. Other mechanisms may still make subjects attend to the irrelevant dimension.

Thus Experiment 3 was designed to investigate if bottom-up processes improve performance in comparative visual search. More specifically, we asked whether a constant irrelevant dimension facilitates comparative visual search more than just a verbal instruction. Again, an efficiency gain would be indicated by a significant decrease in RT, FD, NF, and AT and an increase in SL and SP from Experiment 2 to 3 (in technical terms, one would expect a significant main effect for the factor experiment).

As in the comparisons between Experiment 1 and 2, another issue addressed is the difference between color and form mismatch trials. A differential beneficial effect would result in a significant interaction between the factors experiment and type of mismatch.

4.1. Method

Sixteen new subjects were recruited at the University of Bielefeld. They had normal or corrected-to-normal vision and none of them was color blind or had pupil anomalies. All subjects were paid for their participation.

Apparatus, stimuli, and procedure were identical to those described in Experiment 2. In addition to a verbal cue about the relevant dimension the irrelevant dimension was held constant. (When the picture halves differed in color, all forms were equal; when the picture halves differed in form, all colors were equal). The frequencies of the three forms and the three colors that constituted the irrelevant dimension were balanced.

4.2. Results and Discussion

Aside from the absolute values, the results of Experiment 3 showed a similar pattern as those of Experiment 2. Once again, a difference in RT was found between color and form mismatches: It took subjects 7422 ms to respond when color was the relevant dimension and 9279 ms when form was relevant, $t(15) = 4.28$, $p < 0.005$. FD did not depend on type of mismatch (218.01 ms for color mismatches and 214.66 ms for form mismatches). Saccades were longer when the subjects searched for a color mismatch (58.67 pixels) than when they searched for a form mismatch (56.43 pixels), $t(15) = 2.40$, $p < 0.05$. Even when the irrelevant dimension was held constant, SP was higher for a difference in color (58.78 pixels/s) than for a difference in form (46.57 pixels/s), $t(15) = 4.90$, $p < 0.001$. Type of mismatch affected AT as well: Subjects spent 598 ms due to missing a color mismatch and 1272 ms due to missing a form mismatch, $t(15) = 3.59$, $p = 0.003$. NF differed for color (23.03) and for form mismatches (30.15), $t(15) = 4.08$, $p < 0.005$. As in Experiment 2, the AT difference of 674 ms could not sufficiently explain the overall RT difference of 1857 ms. RT differences and AT differences were unequal, $t(15) =3.30$, $p < 0.01$). Thus, the remaining difference could be attributed to the lower SP when searching for a form mismatch. The results are shown in Figures 2 to 7.

All in all, keeping one dimension constant does not change the relation between color and form mismatch trials. Search for a form mismatch is still harder to accomplish: Saccade length is shorter, search speed is lower, number of fixations is higher, and the additional search time is longer, which results in longer RT.

As for the comparison between experiments, an analysis of variance was performed with the within-subjects factor type of mismatch (color vs. form mismatch) and the between-subjects factor experiment (Experiment 2 vs. Experiment 3).

Again, we shall begin with the main effects of type of mismatch: Type of mismatch exerted a significant influence on all dependent variables, namely RT, $F(1;34) = 43.82$, $p < 0.001$, FD, $F(1;34) = 4.35$, $p < 0.05$, SL, $F(1;34) = 12.40$, $p < 0.005$, NF, $F(1;34) = 48.22$, $p < 0.001$, SP, $F(1;34) = 30.52$, $p < 0.001$, and AT, $F(1;34) = 23.61$, $p < 0.001$. It took less time to detect a color target (7376 ms) than to detect a form target (9910 ms). FD was longer for color search (213.02 ms) than for form search

(209.29 ms). SL was longer for color mismatches (58.74 pixels) than for form mismatches (56.54 pixels). It took fewer fixations to search for a color mismatch (22.60) than to search for a form mismatch (32.65). SP was higher for color mismatches (58.35 pixels/s) than for form mismatches (47.52 pixels/s). Finally, AT was shorter when subjects searched for a color mismatch (708 ms) than when they searched for a form mismatch (1886 ms).

The factor experiment had a significant effect on AT, $F(1;34) = 5.92$, $p < 0.05$. AT decreased from Experiment 2 (1659 ms) to Experiment 3 (935 ms). All other variables were independent of the factor experiment (RT was 8936 ms for Experiment 2 and 8351 ms for Experiment 3; FD was 205.97 ms for Experiment 2 and 216.34 ms for Experiment 3, SL was 57.72 pixels for Experiment 2 and 57.55 pixels for Experiment 3; NF was 28.66 in Experiment 2 and 26.59 in Experiment 3; and SP was 53.20 pixels/s for Experiment 2 and 52.68 pixels/s for Experiment 3).

Comparing Experiments 2 and 3 showed one significant interaction between the factors type of mismatch and experiment, that is, on AT, $F(1;34) = 4.32$, $p < 0.05$. Simple effect analyses indicated an effect by factor experiment only with form mismatch trials, $F(1;34) = 6.44$, $p < 0.05$, and type of mismatch had a reliable effect only with Experiment 2, $F(1;34) = 27.07$, $p < 0.001$, while in Experiment 3 there was just a tendency towards an influence, $F(1;34) = 3.48$, $p = 0.071$.

Conceivably, the variation in Experiment 3 levels the AT values through the influence on form mismatch trials. The only condition that differs significantly from the others is search for form mismatches in Experiment 2: AT is higher. The interaction for RT did not reach significance but showed a tendency in the predicted direction, $F(1;34) = 3.13$, $p = 0.086$, as did the one for NF, that missed significance only slightly, $F(1;34) = 4.09$, $p = 0.051$.

What does this tell us with regard to the assumptions? Holding the irrelevant color dimension constant seems to improve the efficiency of form search, but holding the irrelevant form dimension constant does not seem to improve color search any further than just a verbal instruction about the type of mismatch. In other words, bottom-up processes improve the performance of subjects only when searching for a form target.

5 General Discussion and Conclusions

Earlier studies of the effects of irrelevant stimulus dimensions have come to the conclusion that subjects cannot disregard irrelevant dimensions. In contrast to these investigations, the present study suggests that they can, at least in part. These contradictory results may originate in differences in the experimental procedure: While earlier experiments were aimed at the question, whether or not there are any negative effects of irrelevant dimensions, the aim of the present study was to investigate whether or not particular factors can improve the ability to disregard irrelevant dimensions. As shown above, verbal information about the kind of difference made search more efficient (decrease in RT and number of fixations), in particular when searching for a difference in color (higher SP and, in tendency, longer saccades). Holding the irrelevant dimension constant in addition to verbal information led to an increase in search efficiency for a difference in form (shorter AT, shorter RT, and fewer fixations). These discrepancies in the findings about the effects of irrelevant dimensions indicate that the question whether or not subjects can ignore irrelevant information should be reformulated. Disregarding irrelevant dimensions seems to be a matter of degree rather than an all-or-none process.

After having demonstrated that irrelevant stimulus dimensions can at least partially be ignored, we shall turn to the cognitive processes that take place in selective comparative search. Actually, there are two questions to be considered: First, why does verbal information about the irrelevant dimension lead to a general improvement in efficiency in Experiment 2 as compared to Experiment 1, the improvement being more pronounced when searching for a difference in color? Second, why does a constant color improve efficiency in Experiment 3 as compared to Experiment 2 when searching for a difference in form but why does a constant form not improve efficiency for a difference in color? In other words: Why does variation of the irrelevant dimension color have a negative effect whereas variation of the irrelevant dimension form has not?

Proceeding from one of the basic assumptions of mental chronometry research, namely, that the time interval between the presentation of a stimulus and the subject's reaction is composed of various operations or subprocesses, we may - as a first step - attempt to list the operations or subprocesses that play a role in comparative visual search. For such a coarse list, it does not matter whether the transition between the subprocesses is to be conceived of as discrete [18], continuous [19], cascaded [20], or hybrid [21]. What subprocesses likely play a role in comparative visual search when subjects do not know the relevant or irrelevant dimension in advance, such as in Experiment 1? To begin with, the subject will try and get a coarse overview of the display in order to decide where to start searching (e.g., in a top-down fashion). Next, the subject will analyze the features (such as color and form) of a set of objects in succession or in parallel. As a result, the feature values will be stored in working memory - again, in succession or in parallel. In addition, the position of the objects will be stored to enable the subjects to find the appropriate counterparts in the other display half and to avoid repeated analysis of the same objects (inhibition of return). When working memory is "filled" to capacity, the subject will change to the corresponding area of the other display half. Here, too, the objects will be analyzed as to their features and their values compared to the stored ones. If a difference is found, it is likely to be verified by means of repeated comparison between the display halves. Next, the motor reaction must be programmed and the key press executed. However, if no difference is found, the next set of objects will have to be analyzed as to their features, the values be stored and compared to those of the corresponding objects in the other half of the display, and so forth. Finally, if they have searched the whole display without detecting a difference, subjects will have to go through the whole search process anew.

Which of these subprocesses in the comparative search for a difference in color or in form will be affected by additional verbal information about the relevant dimension, as in Experiment 2? Strictly speaking, the subjects would only have to process the relevant dimension. Since any subprocesses prior to the identification of objects likely proceed automatically, we suppose that Experiment 2 differs from Experiment 1 mainly in the storage and comparison subprocesses. Storage and comparison could be restricted to the relevant dimension, irrespective of whether color or form is relevant. With less information to be analyzed per object, in effect, less time per object would be required for storage, and sufficient information about more objects could be stored in working memory during each processing cycle, that is, before switching to the other display half. In addition, comparison would take less time. The view that subjects, with each fixation, pick up information about more objects in Experiment 2 than in Experiment 1, is substantiated by the fact that the number of fixations but not their duration decreases from Experiment 1 to Experiment 2.

Moreover, we suppose that there are fundamental differences in the perception of color and the perception of form. Color is more salient than form. Aside from neurophysiologic considerations, one reason for this might lie in the following: After fixating on a new area of the stimulus display, information about color will earlier be available to further cognitive processing than information about form. Hence color information will more readily be used as a basis for the structuring of the percept than form information. This view is in line with results of [22]. According to their approach, visual search begins with the processing of the stimulus at a level of low spatial frequency. Subsequently, the spatial frequency is increased step by step, which leads to new, and more, fixations. This account is suited to model human gaze trajectories statistically with a high degree of fit. With stimuli of the kind used in comparative visual search, only color can be evaluated while operating at low spatial frequency. Evaluation of form requires a higher level of spatial frequency. So, in the course of processing, color information can be utilized earlier than form information (cf. Figure 8). Color takes precedence over form. In consideration of this, we assume that color is stored as a global pattern (or gestalt), whereas form is stored as a pattern only if color is homogeneous.

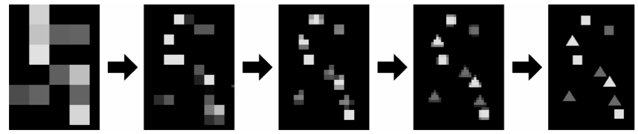

Figure 8: Available information from a part of the example stimulus at different time stages according to the assumption of multiscale spatial filters

As color can be processed faster than form, the increase in search efficiency is more pronounced when a difference in color is to be detected than when a difference in form is to be detected. Average search speed is increased and the average length of saccades is increased at least in tendency. Also, the numerical values to be observed for the number of fixations and the overall reaction time are in line with the considerations outlined above: The increase in search efficiency is most pronounced for differences in color.

Finally, which subprocesses are affected by additionally holding constant the irrelevant dimension when people search for a difference in form, such as in Experiment 3? Holding constant the irrelevant color reduces the search time due to overlooking of the difference in color; hence there is a decrease in the number of fixations and the reaction time. To summarize, a constant color makes overlooking of a difference in form less likely while a constant form does not make overlooking of a difference in color less likely. Inversely, it follows that variation of color must facilitate overlooking of form differences while variation in form will take no effect on overlooking color differences. This can be explained on the basis of the view sketched above, namely, that color takes precedence and is represented as a global pattern which can be memorized and compared in a single step. Thus, color information is well preserved, and color values will scarcely become associated with the wrong location. In effect, it is relatively easy to detect the difference. If, however, forms rather than colors have to be stored and compared, matters are different. Being tied to specific objects, form information could quite easily perish in the course of comparison, or form values be associated with the wrong location. This may serve as an explanation why in Experiment 2 form differences are overlooked more frequently. However, when the irrelevant color is held constant, form is the dimension which may take precedence and which can be stored as a pattern, without "distraction" by a varying color. Conversely, a constant form does not enhance color search any more than does verbal information, because color is stored as a global pattern, regardless of whether or not form is held constant.

Further research is needed to investigate the difference between color and form. In particular, it should be studied if color takes precedence generally or if using a set of more or less distinct colors would change the pattern of findings. If the latter were true, one would have to assume that form would take precedence and would be stored in a global fashion while, on the other hand, global processing of color would require a constant form.

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